TR-225

TECHNICAL REPORT

ASWEPS REPORT NO. 18

NUMERICAL METHODS OF PREDICTING THE NORTHERN EDGE OF THE GULF STREAM

APRIL 1971

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A B S T R A C T

Four numerical simulation methods were examined in an effort to predict the variation in positoin of the Gulf Stream's northern edge. The first two methods, application of river meander theory to Gulf Stream meanders and relating the Gulf Stream to paths of constant potential vorticity in barotropic flow, proved unsatisfactory for Gulf Stream prediction. The second two methods, prediction by harmonic analysis and a simple barotropic dynamic model, appear adequate for short-term (less than 10 days) prediction.

WILLIAM H. GEMMILL

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FOREWORD

The Naval Oceanographic Office is conducting comprehensive descriptive investigations of the thermohaline structure in the western North Atlantic. These investigations aid in understanding physical properties of ocean areas. One of the goals of these studies is prediction of the thermal structure using empirical and dynamic methods.

This report presents four methods used to numerically simulate and predict Gulf Stream meandering, a dominant feature of the western North Atlantic. Other models being developed deal with warm and cold eddies, the slope frontal system, and the seasonal aspects of heating and cooling. The objective of these investigations is to provide the Fleet with a means for real-time prediction of significant operational environmental factors.

F. L. SLATTERY
Captain, U.S. Navy
Commander

CONTENTS

A. INTRODUCTION

During the past four years, the U. S. Naval Oceanographic Office has been conducting airborne oceanographic research surveys of the western North Atlantic Ocean including mapping the position of the Gulf Stream's northern edge. As these data became available, statistical studies were made of certain characteristics of the Gulf Stream, such as its mean path, speed of its meanders, and the limits of its northern edge. At the same time, attention was turned to applying and testing methods for predicting the Gulf Stream's northern edge.

This paper describes four numerical simulation methods for predicting the Gulf Stream's northern edge as follows: (1) application of river meander theory to Gulf Stream meanders, (2) the relation of the Gulf Stream to paths of constant potential vorticity, (3) movement of harmonic components of Gulf Stream meanders using a dispersive wave equation, and (4) a simple dynamic model of the Gulf Stream by numerical integration of the vorticity equation. Brief descriptions of these methods have appeared in the Gulf Stream Summary (6, 7, 8, 9, 10).

B. MATHEMATICAL SIMULATION METHODS

1. Application of River Meander Theory to Gulf Stream Meanders

Leopold and Langbein (2) described a mechanism for river meanders which appeared to be feasible as a mechanism for generating Gulf Stream meanders. River meanders can be simulated by curves that require a minimum of work in turning. Such curves have maximum radii of curvature and can be derived by minimizing the integral of energy required to alter the direction of the river. These curves can be closely approximated by sine-generated curves, i.e., the tangential direction of the resulting curves varies sinusoidally.

Figure 1(a) shows an example of a sine-generated curve, and figure 1(b) shows the direction plotted as a function of distance downstream. Angles are measured from the direction of the mean path, positive to the left and negative to the right. Since the tangential direction varies sinusoidally,

$$\alpha = \mu \cos \frac{2\pi S}{D} \tag{1}$$

where:

α = tangential direction of curve at some point along curve

μ = maximum angle of deflection [e.g., at points 1, 3, 5, and 7 in figure 1(a), where $\alpha = 90°$]

S = distance measured along curve from the starting point

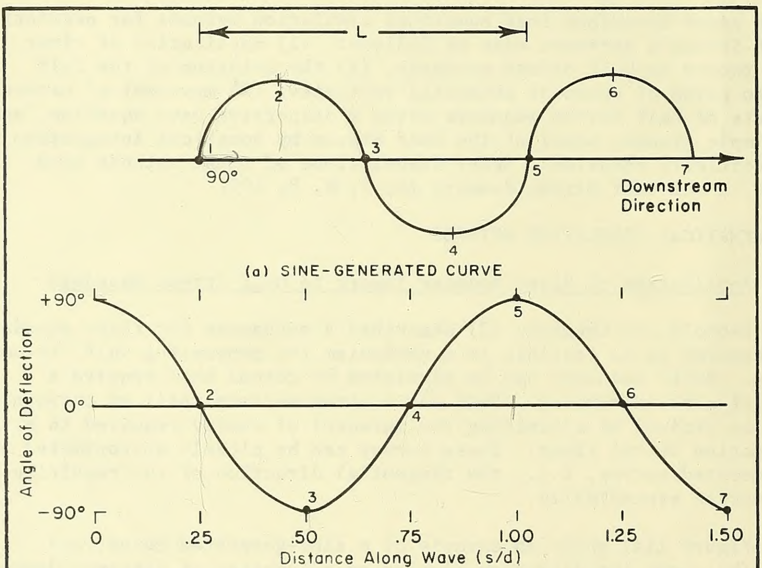
D = ~~distance~~ total length along the wave [e.g., ~~through~~ from points 1 to 5 in figure 1(a)]

The following relations are given by mathematical approximations:

$$\sin \alpha \approx \Delta y/\Delta S \qquad (2a)$$

$$\cos \alpha \approx \Delta x/\Delta S \qquad (2b)$$

where ΔS, Δx, and Δy are the distance between computed points along the meander, the x component of ΔS, and the y component of ΔS, respectively.



(a) SINE-GENERATED CURVE

(b) ANGLE OF DEFLECTION ALONG SINE-GENERATED CURVE — POSITIVE TO LEFT, NEGATIVE TO RIGHT

Figure 1. A Sine-Generated Curve

A sine-generated curve can be produced as a series of points by solving equations (1) and (2). Given the maximum angle of deflection (μ), the distance increment between points (ΔS), and the distance along one wave (D), and assuming that at the starting point $x_0 = y_0 = S = 0$, the direction (α) of the curve can be determined from equation (1). Then equation (2) will give Δx and Δy, and the new point becomes $x_1 = x_0 + \Delta x$ and $y_1 = y_0 + \Delta y$. Thus, by iteration, a succession of points along the curve is determined.

These curves are conservative, i.e., they do not grow or change downstream. The Gulf Stream has been observed to leave the Cape Hatteras area with little tendency to meander; however, as the stream progresses into the open ocean, meanders become larger and larger, indicating greater angles of maximum deflection. A modification which allows the angle of maximum deflection to increase linearly along the path is given by:

$$\mu' = \mu + (\Delta\mu)\ S/D \tag{3}$$

where μ' = the modified maximum angle, and $\Delta\mu$ = the change of the maximum angle of deflection along one wave. Because the wavelengths become shorter as the angle of maximum deflection increases, an additional modification was required; therefore ΔS, the distance between points, was also made to increase linearly along the path.

$$\Delta S' = \Delta S + [\Delta(\Delta S)]\ S/D \tag{4}$$

where $\Delta S'$ = modified distance between points anywhere along the curve and $\Delta(\Delta S)$ = the amplification factor which is the increase in the distance between points along one wave. Equations (1) and (2) may now be rewritten using these new modifications substituting μ' for μ and $\Delta S'$ for ΔS.

Several examples of modified sine-generated curves are presented in figure 2. In this figure, the change in angle of maximum deflection and the distance increment amplification factor are indicated over the entire path of the wave. In these examples, the curves are followed through five waves.

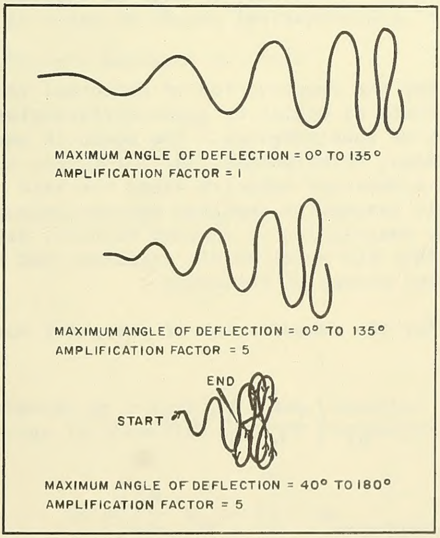


Figure 2. Examples of Modified Sine-Generated Curves

An attempt to fit an amplifying sine-generated curve to an observed Gulf Stream path is shown in figure 3. The Gulf Stream, however, does not behave as a river and the application of the river meander theory to Gulf Stream meanders was not satisfactory. The fact that modifications of the pure sine-generated curves were necessary indicates that the interaction of dynamic forces of the Gulf Stream system are not adequately satisfied by simply minimizing the work required in turning.

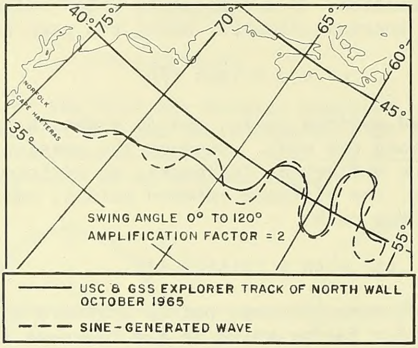


Figure 3. A Modified Sine-Generated Curve Compared to the Gulf Stream

2. Relating Gulf Stream Meanders to Paths of Constant Potential Vorticity

Warren (11) demonstrated that meanders of the Gulf Stream appear to conserve potential vorticity. That is, the flow of the Gulf Stream responds primarily to changes in bottom topography and to a lesser extent latitude. Using this hypothesis, a model is described for use in calculating the path of a hypothetical parcel of water as it leaves the Cape Hatteras region.

The equation for the conservation of potential vorticity is derived from the equations of motion by cross-differentiation and by imposing the condition of nondivergence. The ocean is assumed to be incompressible, homogeneous, frictionless, and barotropic under steady state conditions with a constant velocity along the axis of the Gulf Stream. The barotropic assumption requires current velocity to be constant with depth. The restriction on current velocity differs from that imposed by Warren in that his model merely required that the current extend to bottom without change of direction.

The equation for the conservation of potential vorticity can be written:

$$\frac{d}{dt}\left(\frac{\zeta + f}{h}\right) = 0 \tag{5}$$

where:

ζ = relative vorticity
f = Coriolis parameter
h = ocean depth

Integration of equation (5) with respect to time gives:

$$\frac{\zeta + f}{h} = \frac{\zeta_0 + f_0}{h_0} = \text{constant} \tag{6}$$

where ζ_0, f_0 and h_0 are initial values. The relative vorticity can be expressed by:

$$\zeta = \frac{\partial V}{\partial n} + \frac{V}{R} \tag{7}$$

where:

V = the current velocity

R = the radius of curvature

V/R = rate of turning by the current

$\partial V/\partial n$ = horizontal velocity shear normal to the current

Assuming no horizontal shear, which is the same as stating that the current is infinite in width, then ($\partial V/\partial n=0$). Starting at an inflection point in the flow, using equation (7), and assuming that $\partial V/\partial n=0$, equation (6) is simplified:

$$\zeta = \frac{h}{h_0} f_0 - f \tag{8}$$

Equations (7) and (8) are combined to give:

$$R = V/\left(\frac{h}{h_0} f_0 - f\right) \tag{9}$$

Further, using the mathematical relations:

$\Delta\Theta \approx \Delta S/R$

and

$V = \Delta S/\Delta t$

where ΔS is approximated by a straight line, equation (9) is now written in terms of the change in direction ($\Delta\Theta$) as the parcel of water moves between two points.

$$\Delta\Theta = \left[\left(\frac{h}{h_0} f_0\right) - f\right] \quad \Delta t \tag{10}$$

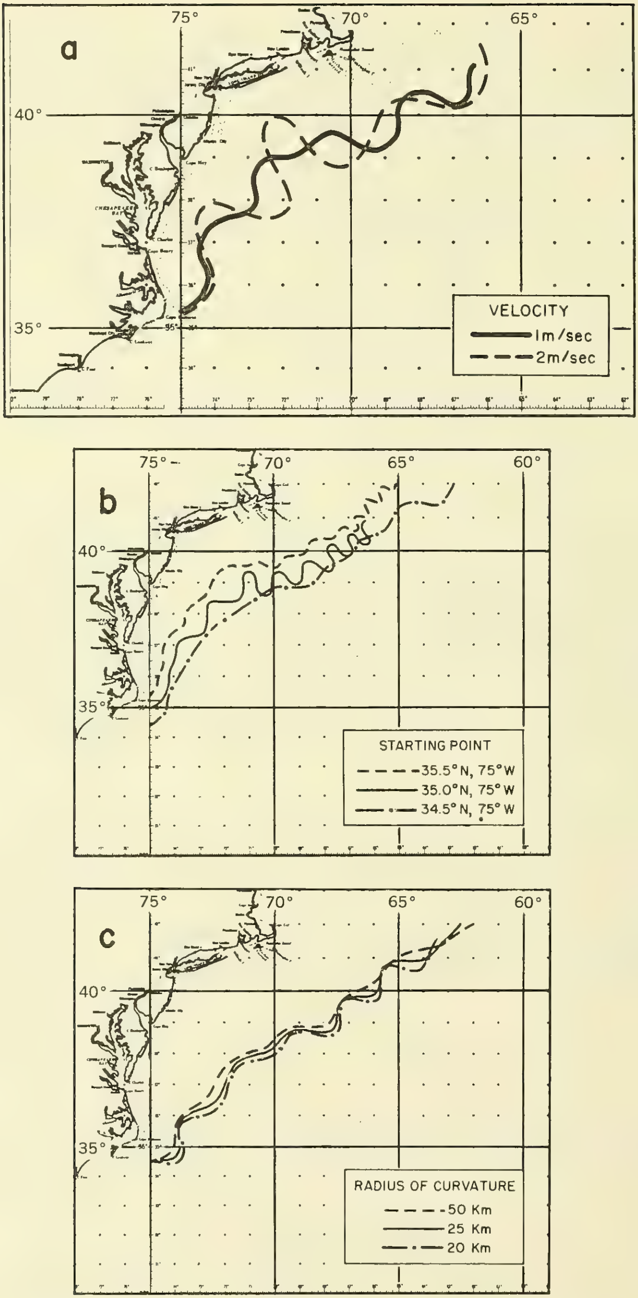


Figure 4. Paths of Constant Potential Vorticity

Current velocity is assumed to remain constant along the path. Given the initial latitude and longitude at the starting point, the initial depth of the ocean, the velocity of the current, the initial direction, and the time interval between points, a parcel of water is followed from the initial point P_0 to point P_1, using equation (2). The direction (Θ) of the current will remain constant during the time interval (Δt), if the time interval is small enough. The parcel of water follows a new direction (Θ_1) from point P_1 to point P_2, $\Theta_1 = (\Theta_0 + \Delta\Theta/2)$, where Θ_0 was the direction from P_0 to P_1, and $\Delta\Theta$ is determined from equation (10). The above procedure is repeated to find P_3, P_4, etc.

Several experimental tests are shown in figures 4 and 5. The time interval (Δt) is 10 minutes. Figure 4a shows paths computed with current speeds of one and two m/sec. These speeds are unrealistic, since the actual vertically averaged horizontal speed probably lies between 25 and 50 cm/sec. Using the lower speed of 25 cm/sec, the path of the Gulf Stream was examined by varying the starting point (figure 4b) and by varying the initial curvature (figure 4c). The assumptions for the flow of the Gulf Stream are apparently inadequate. In all of these tests (variation of the mean vertically averaged speed, variation of the starting location, and variation of the initial radius of curvature), the calculated paths do not represent observed paths of the Gulf Stream. The predicted position is too far north.

Since the Gulf Stream current is variable with depth, strongest near the surface and weakest near the bottom, the control of bottom topography should be weighted in order to account for the difference between the mean flow and the bottom flow. This is accomplished by replacing h/h_o in equation (10) by the weighting expression $W_B(h-h_o/h_o)+1$. For the full effect of the ocean's variable depth, $W_B=1$; and for no effect, $W_B=0$. This weighting expression essentially reduces the influence of the topographic gradient along the path. Figure 5 shows a configuration of the Gulf Stream generated with different weights given to bottom topography. The less the influence of the bottom, the more easterly the path of the stream. In the case of a flat-bottomed ocean, the paths become Rossby-type waves.

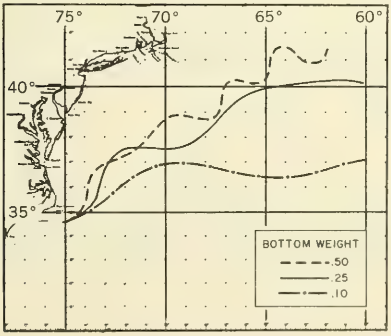


Figure 5. Effects of Bottom Topography on Gulf Stream Path

3. Prediction of Gulf Stream Meanders Using Harmonic Components

Observations of the northern edge of the Gulf Stream show a system of long waves which usually move toward the east. If these waves are assumed to be similar to atmospheric waves, the Rossby wave theory asserts that in an eastward flowing current the shorter waves should move the most rapidly eastward, that longer waves should remain nearly stationary, and that the longest waves will retrogress. Thus the wave system of the Gulf Stream is treated as dispersive.

The harmonic component prediction method is accomplished by first digitizing the observed wave-like northern edge of the Gulf Stream relative to the historical mean axis. The digitized curve is then resolved into its first 10 harmonic components to find the amplitude of each harmonic. Using a dispersive wave equation to find movement of each harmonic wave through a prediction period, the predicted Gulf Stream position is determined by recombining the components.

The Gulf Stream was digitized by measuring at equal intervals of x (along the mean position) the normal distance (Y) to the observed position of the Gulf Stream. In order to avoid unreal amplitude of the first harmonic, the mean axis was adjusted by adding or subtracting a constant to Y, so that area enclosed by the curve above the axis equals the area below.

After the Gulf Stream was digitized, the amplitudes (A,B) of each harmonic component were determined by:

$$A_i = \frac{2}{N}\sum\left[Y \sin \frac{2\pi ix}{L}\right] \; ; \; B_i = \frac{2}{N}\sum\left[Y \cos \frac{2\pi ix}{L}\right] \tag{11}$$

where:

L = total length of the Gulf Stream path along the mean axis of flow (also length of first harmonic)

N = total number of points along x-axis

i = harmonic number (i = 1, 2, ..., 10)

x = length along axis from origin

Y = normal distance of the historical mean axis from observed track

Next, the phase speed (C_i) of each harmonic wave was determined by the dispersive Rossby wave equation:

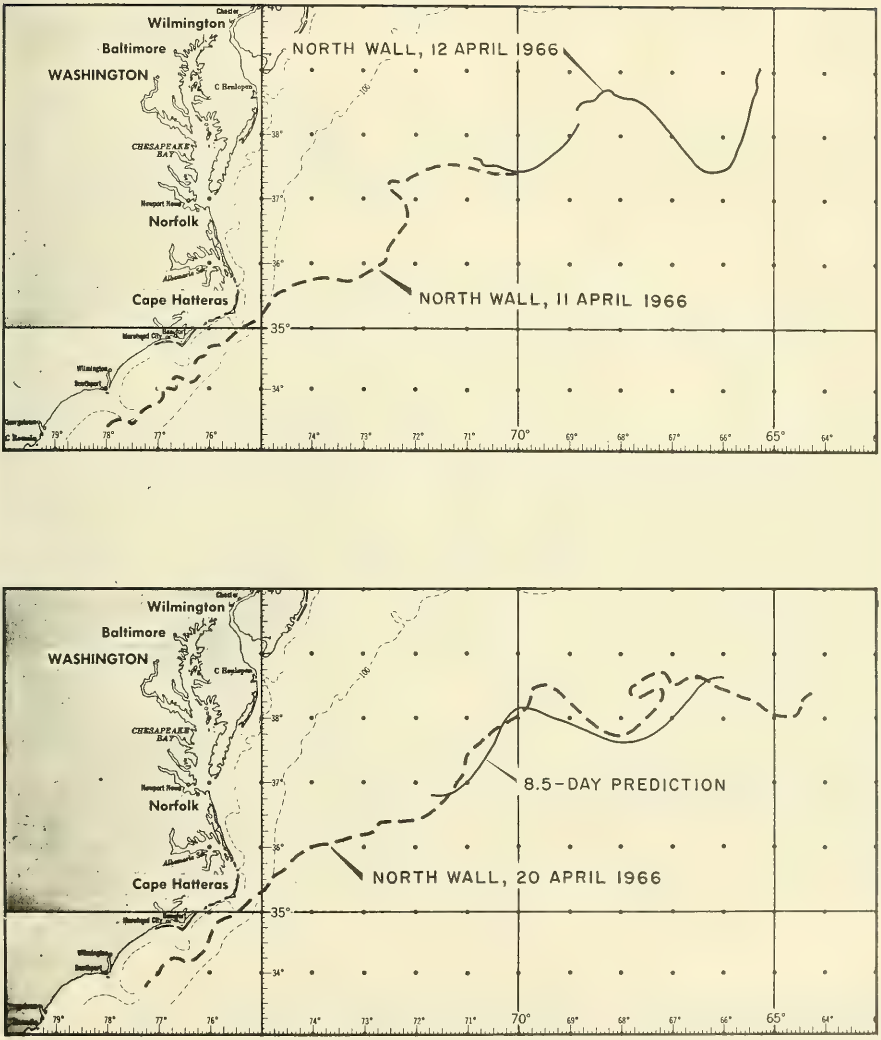


Figure 6. Comparison of an Harmonic Prediction With Observed Gulf Stream

$$C_i = U - \frac{\beta L^2}{4\pi^2 i^2} \tag{12}$$

where:

β = change of Coriolis parameter to the north
U = velocity of the mean flow (30 cm/sec)

Since the amplitudes of the sine and cosine components of each harmonic and the phase speed of each harmonic are known, the position of the northern edge of the Gulf Stream can be predicted at some time (t) by:

$$Y = \overline{Y} + \sum_{i=1}^{10} A_i \sin \frac{2\pi i}{L} (x - c_i t) + \sum_{i=1}^{10} B_i \cos \frac{2\pi i}{L} (x - c_i t) \tag{13}$$

An example of an harmonic prediction of the Gulf Stream compared to its measured position is shown in figure 6. The position of the northern edge of the Gulf Stream was established during two flights on 11 and 12 April 1966. The prediction was made for 8.5 days later on 20 April, for which observed data are also plotted. Because this method conserves energy in each component, development of large loops and eddies is not possible.

4. Prediction of Gulf Stream Meanders by Dynamic Two-Dimensional Advection

The above methods are essentially one-dimensional, with the Gulf Stream represented by a line. The general features and circulation of a region as well as positions of specific features are also of interest. A two-dimensional ocean model similar to the model used in the second method was used for Gulf Stream prediction. The ocean is homogeneous, frictionless, and barotropic, with the added restraints of a horizontal bottom and top and bounds of 33°N, 42°N, 65°W, and 79°W. The area is subdivided into a 20-km grid. The vertically integrated vorticity equation is given by:

$$\frac{d}{dt} (\zeta + f) = 0 \tag{14}$$

This is the equation for conservation of absolute vorticity. The vorticity equation (14) is rewritten as:

$$\frac{\partial \zeta}{\partial t} = - \vec{V} \cdot \vec{\nabla} (\zeta + f) \tag{15}$$

Assuming the flow to be nondivergent, the stream function (Ψ) is introduced by definition as:

$$u = -\frac{\partial \Psi}{\partial y}, \quad v = \frac{\partial \Psi}{\partial x}$$

the **vorticity** equation (15) is then rewritten using the stream function (Ψ):

$$\nabla^2 \frac{\partial \Psi}{\partial t} = \frac{\partial \Psi}{\partial y}\frac{\partial(\nabla^2\Psi)}{\partial x} - \frac{\partial \Psi}{\partial x}\frac{\partial(\nabla^2\Psi)}{\partial y} - \frac{\partial \Psi}{\partial x}\frac{\partial f}{\partial y} \tag{16}$$

The equation is transformed into centered spaced finite differences and is solved for $\partial\Psi/\partial t$ at each grid point by numerical relaxation on the 20-km grid at 6-hour time intervals. In addition, the stream functions along the boundaries were adjusted so that the net transport of vorticity across the boundaries was balanced. A further simplification was made in this preliminary test by assuming a uniformly rotating ocean, the Coriolis parameter is constant, and $\partial f/\partial y = 0$ in equation (16).

The prediction was accomplished as follows. The observed northern edge of the Gulf Stream was drawn on a 20-km grid. This line was given a stream function value of zero. A series of stream function lines were drawn south of this line to correspond to a Gulf Stream with a mean horizontal velocity of 50 cm/sec and a width of 100 km. To the north of the Stream, the grid was filled with zeroes; to the south, the grid was filled with the maximum value of the stream function which occurred along the southern edge of the Gulf Stream. The resulting flow field is unrealistic since it is discontinuous, i.e., no flow occurs north or south of the stream with 50 cm/sec in the stream. This discontinuity creates both physical and mathematical problems.

The prediction of the new stream function values at each grid point was accomplished using the first-forward-then-centered time differencing method in the following forms:

forward time differences:

$$\Psi_{\tau+1} = \Psi_{\tau} + \left(\frac{\partial \Psi}{\partial t}\right)_{\tau} \Delta t$$

centered time differences:

$$\Psi_{\tau+1} = \Psi_{\tau-1} + 2\left(\frac{\partial \Psi}{\partial t}\right)_{\tau} \Delta t$$

where $\Psi_{\tau+1}$ is predicted value, Ψ_{τ} and $(\partial\Psi/\partial t)_{\tau}$ are the present or calculated values, and $\Psi_{\tau-1}$ is the value from the previous time step. The forward time difference is used only for the first time interval, thereafter the centered time difference is used. In addition, the computational

stability criteria requires that $V < \Delta x/\Delta t$, which limits the maximum current in this model to about 92 cm/sec before the solutions become unstable.

Several problems were immediately apparent in this model. The fixed outflow along the eastern boundary was so restrictive that waves could not move across the boundary, therefore instabilities eventually developed. To eliminate this problem, the eastern boundary was extrapolated eastward to 50°W. Also, the Gulf Stream was noted to widen with time owing, in part, to a nonlinear effect created by the unreal cross-stream current profile.

The prediction model was run for short prediction periods (up to 10 days). A sample prediction and verification is shown in figure 7.

C. CONCLUSION

None of these methods is entirely satisfactory for Gulf Stream prediction, since each method requires rather simplified assumptions about the ocean. However, each method attempted to isolate a particular physical relation as a predictor for Gulf Stream positions.

The first two prediction methods, (1) application of a river meander theory to Gulf Stream meanders, and (2) the relation of Gulf Stream meanders to paths of constant potential vorticity in a barotropic flow, were not adequate for simulating observed paths of the Gulf Stream. The remaining two methods, the harmonic and barotropic prediction models, appear adequate for short-term (less than 10 days) prediction. Either of the latter methods can be implemented to aid in the analysis of synoptic oceanographic charts. Present methods of analysis give an uncertain position of the northern edge of the Gulf Stream unless airborne data are available for establishing its location. Thus, the above methods could be used for estimating the position of the stream between aircraft flights.

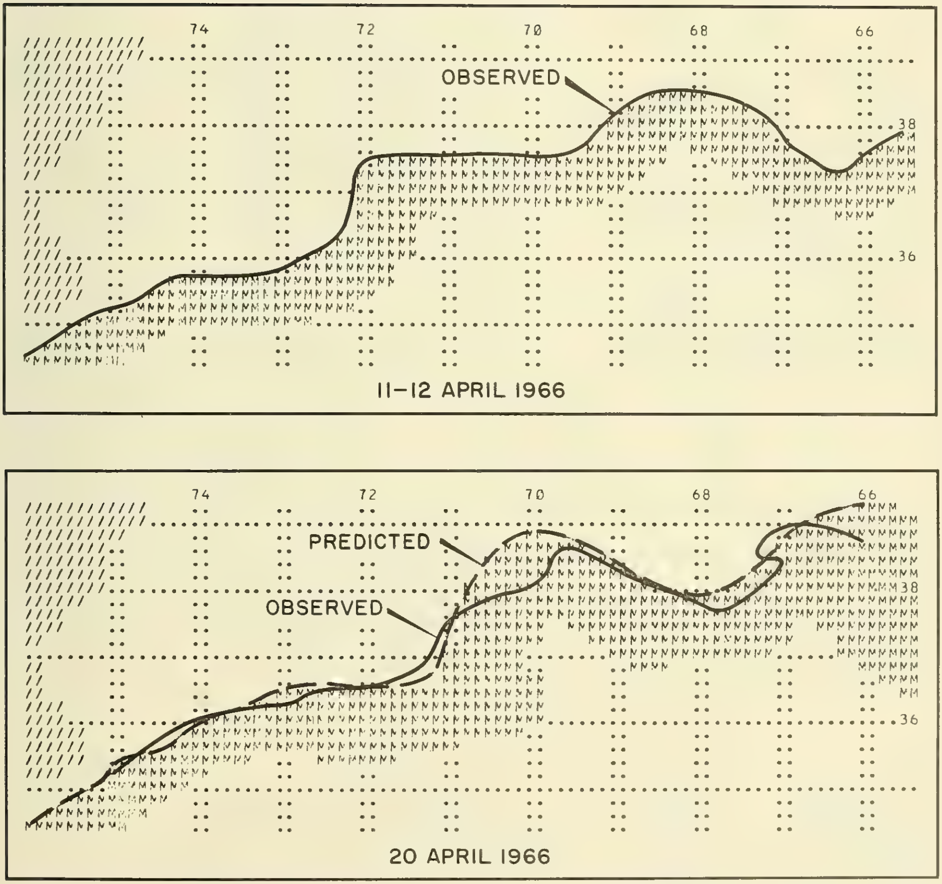


Figure 7. Comparison of a Barotropic Prediction With Observed Gulf Stream

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ABSTRACT

Four numerical simulation methods were examined in an effort to predict the variation in position of the Gulf Stream's northern edge. The first two methods, application of river meander theory to Gulf Stream meanders and relating the Gulf Stream to paths of constant potential vorticity in a barotropic flow, proved unsatisfactory for Gulf Stream prediction. The second two methods, prediction by harmonic analysis and a simple barotropic dynamic model, appear adequate for short-term (less than 10 days) prediction.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
DYNAMIC PREDICTION						
GULF STREAM						
GULF STREAM PREDICTION						
HARMONIC ANALYSIS						
MATHEMATICAL ANALYSIS						
NORTH ATLANTIC OCEAN						
NUMERICAL PREDICTION						
OCEANOGRAPHY						
POTENTIAL VORTICITY						
RIVER MEANDER						
SINE-GENERATED CURVES						